UNIQUENESS THEOREMS FOR TAUT SUBMANIFOLDS

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1. Introduction and statements of theorems. Given two closed smooth manifolds, how do you tell if they are diffeomorphic? If you start out with a homotopy equivalence, Browder–Novikoff Theory breaks the problem up into: (1) finding all self-equivalences, (2) finding a normal bordism, and (3) the surgery obstruction on the normal bordism. In applications, however, one may encounter manifolds suspected of being diffeomorphic, where no obvious homotopy equivalence is present.

We describe such a situation: Let $I$ be a simply connected, finite, simplicial complex with linear bundle. Let $K_i^n \rightarrow M$, $i = 0$ or 1, $n \geq 3$, be normal maps from closed smooth manifolds, i.e. $f^*(\xi) = \nu(K_i)$. Suppose that $f_1$ and $f_2$ are normally bordant, $f_i$ is $n$-connected, and that $B_n(K_0) = B_n(K_1)$. $B_n$ here denotes the $n$-th Betti number. It follows from Poincaré’s Duality and the universal coefficient theorem that $K_0$ and $K_1$ have isomorphic integral homology groups, but a map inducing this isomorphism is lacking. However,

**THEOREM 1.** If $n$ is odd, $K_0$ and $K_1$ are diffeomorphic.

**THEOREM 2.** If $n$ is even, but not 2, and the intersection pairings on

$$(\text{Ker } f_0: H_n(K_0; \mathbb{Z}) \rightarrow H_n(M; \mathbb{Z})/\text{torsion}) \quad \text{and} \quad (\text{Ker } f_1: H_n(K_1; \mathbb{Z}) \rightarrow H_n(M; \mathbb{Z})/\text{torsion})$$

are isometric and nonsingular, then $K_0$ and $K_1$ are diffeomorphic.

**COROLLARY 1.** If $M^{2n+2}$ is a compact, simply connected, smooth $2n+2$-manifold, $n$ odd, and $K_0^{2n} \rightarrow M^{2n+2}$ and $K_1^{2n} \rightarrow M^{2n+2}$ are $n$-connected inclusions of closed submanifolds with $i_0[K_0] = i_1[K_1] \in H_{2n}(M^{2n+2}; \mathbb{Z})$, then if $B_n(K_0) = B_n(K_1)$, $K_0$ is diffeomorphic to $K_1$.

**COROLLARY 2.** Assume $M^{2n+2}$ is a simply connected smooth $2n+2$-manifold, $n$ even ($n \neq 2$), with $H_n(M; \mathbb{Z}) = 0$. If $i_0$ and $i_1$ are as above, then if the intersection pairings on $H_n(K_0; \mathbb{Z})/\text{torsion}$ and $H_n(K_1; \mathbb{Z})/\text{torsion}$ are isometric, $K_1$ is diffeomorphic to $K_2$.

**REMARK 1.** The above corollaries are specialized by replacing the
connectivity assumptions with the assumption that the submanifolds are taut (definition: \( \pi_i \) \( (M\)-neighborhood \((K), \partial) = 0, i \leq n \)).

**Remark 2.** It follows from Corollary 1 and [2] that if \( n \) is odd and \( \pi_i(M^{2n+2}) = 0 \), every homology class \( X \in H_{2n}(M^{2n+2}; Z) \) is represented by a simplest submanifold with an \( n \)-connected inclusion map, \( K^0 \), and every other submanifold with an \( n \)-connected inclusion map is diffeomorphic to \( K^t = K^0 \# S^n \times S^n \times \# \cdots \# S^n \times S^n \), \( t \geq 0 \).

**Theorem 3.** If \( \pi_1(M^{2n+2}) = 0 \), and if \( K_0 \) and \( K_1 \) are submanifolds representing \( X \in H_{2n}(M^{2n+2}; Z) \) with \( n \)-connected inclusion maps, then there are integers \( j, k \) such that \( K_0 \# S^n \times S^n \# \cdots \# S^n \times S^n \) is diffeomorphic to \( K_1 \# S^n \times S^n \# \cdots \# S^n \times S^n \).

**2. Proofs.** (All coefficients will be integral unless stated.)

*Proof of Theorem 1.* Let \( L, \partial L = K_0 \cup -K_1 \), be a normal bordism. By Theorem 1.2 [4] we may assume \( f: L \to M \) is \( n \)-connected. It follows that \( H_*(L, K_0) = 0 \) for \( * \neq n, n + 1 \). Our plan is to perform some normal \( n \)-surgery on interior \((L)\) to produce \( L' \) with \( H_*(L', K_0) = 0 \) (this will leave \( H_*(L, K_0) \) unchanged \(* \leq n - 1\) ). By duality and U.C.T. \( H_*(L', K_0) = 0 \), and \( L \overset{\text{diff}}{\cong} K_0 \times I \overset{\text{diff}}{\cong} K_1 \overset{\text{diff}}{\cong} K_0 \) by the \( h \)-cobordism theorem.

Let \( i_0: K_0 \to L \) and \( i_1: K_1 \to L \) be the inclusions. Consider the following commutative diagram:
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We will consider the two modules identified.

Duality and the U.C.T. show \( H_n(L,K_0) \) and \( H_n(L,K_1) \) are isomorphic. So we have a noncommutative diagram:

\[
\begin{array}{cccccc}
0 & \to & 
\ker f_{n|\partial^*(\ker f_{0_n})} & \to & 
\ker f_{n|\partial^*(\ker f_{0_n})} & \to & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
H_{n+1}(L) & \xrightarrow{f_{n+1}} & H_{n+1}(M) & \xrightarrow{id} & H_{n+1}(M) & \xrightarrow{i_0^*} & H_n(L) & \xrightarrow{f_n} & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
H_{n+1}(K_0) & \xrightarrow{f_{0_{n+1}}} & H_{n+1}(M) & \xrightarrow{id} & H_{n+1}(M, K_0) & \xrightarrow{i_0^*} & H_n(K_0) & \xrightarrow{f_{0_n}} & H_n(M) & \xrightarrow{0} \\
\end{array}
\]

Since \( f_0 \) factors through \( i_0 \), \( \ker (f_{0_{n+1}}) \xrightarrow{id^*} \ker (f_{n+1}) \) is epi. There is a short exact sequence

\[
0 \to \ker (f_{n+1})/\ker (f_{0_{n+1}}) \to \frac{H_{n+1}(M,L)}{i_0^*H_{n+1}(M,K_0)} \to \ker f_{n|\partial^*(\ker f_{0_n})} \to 0
\]

so there is a natural isomorphism

\[
\ker f_{n|\partial^*(\ker f_{0_n})} \cong H_n(L, K_0).
\]

We will consider the two modules identified.

Duality and the U.C.T. show \( H_n(L, K_0) \) and \( H_n(L, K_1) \) are isomorphic. So we have a noncommutative diagram:

\[
\begin{array}{cccccc}
\text{epi} & \pi_0 & \text{ker } f_{n|\partial^*(\ker f_{0_n})} & = & C_0 \\
& \downarrow & \downarrow & & \downarrow & & \downarrow \\
A = \ker f_n & \xrightarrow{\text{epi} \pi_1} & \text{ker } f_{n|\partial^*(\ker f_{0_n})} & = & C_1 \\
\end{array}
\]

We need an algebraic fact about such diagrams.

**Lemma 1.** If \( F \) is a field, there are elements \( a_1, \ldots, a_k \in A \), such that \( \{\pi_\epsilon(a_1) \otimes 1, \ldots, \pi_\epsilon(a_k) \otimes 1\} \) is a basis for \( C_\epsilon \otimes_z F \), \( \epsilon = 0 \) or \( 1 \).

**Proof.** By induction. \( \dim_F (C_0 \otimes_z F) = \dim_F (C_1 \otimes_z F) \). Suppose \( a_1 \cdots a_i \) are already chosen so that \( \pi_\epsilon(a_i) \otimes 1, \ldots, \pi_\epsilon(a_i) \otimes 1 \) are independent. Let the spans of these vectors be \( \text{span}_{j,0} \) and \( \text{span}_{j,1} \). If these spans are proper subspaces of \( C_0 \otimes_z F \) and \( C_1 \otimes_z F \), then \( \pi_\epsilon^{-1}(\text{span}_{i,\epsilon}) \) are proper subspaces of \( A \otimes_z F \). Let \( a_{i+1} \) be any element of \( A \) such that \( a_{i+1} \otimes 1 \in (A \otimes_z F - (\bigcup_{\epsilon=0,1} \pi_\epsilon^{-1}(\text{span}_{i,\epsilon}))) \neq \emptyset \).

In order to compute the effect on \( H_n(L, K_0) \) of normal \( n \)-surgeries along \( L \), we use a diagram adapted from Lemma IV.3.2 [1]. (At this
point it may be helpful for the reader to review the proof that the odd dimensional simply connected surgery obstruction vanishes, see Ch. IV, §3 of [1]. This argument is originally due to J. Milnor and M. Kervaire, see [3].

**Lemma 2.** If $L'$ results from a normal surgery on $S^n \hookrightarrow L$, $[S^n] = x \in \ker f_*$, we have the following diagram:

\[
\begin{array}{cccccc}
H_{n+1}(L', K_0) & \xrightarrow{} & Z \xrightarrow{} & H_n(L_0, K_0) & \xrightarrow{i_*} & H_n(L, K_0) \\
\downarrow & & \downarrow d' & & \downarrow i'_* & \xrightarrow{} & 0 \\
Z \xrightarrow{\lambda'} & & H_n(L_0, K_0) & & H_n(L_0, K_0) & \\
\downarrow & & \downarrow i_* & & \downarrow & \\
H_n(L_0, K_0) & & H_n(L_0, K_0) & & \xrightarrow{0} & \\
\end{array}
\]

with: (1) $\pi_0(x) = x_0 = i_*d(\lambda')$, where $\lambda'$ is the appropriate generator above. (2) The map $\theta: H_{n+1}(L, K_0) \rightarrow Z$ is given by intersection with $\pi_1(x) \in H_n(L, K_1)$.

**Proof.** (1) See Lemma IV.3.2 [1].
(2) $\theta: H_{n+1}(L, K_0) \rightarrow Z$ may be thought of as:

\[
H_{n+1}(L/K_0) \xrightarrow{j} H_{n+1}(L/K_0, L_0/K_0) \xrightarrow{\text{exc}^{-1}} H_{n+1}(S^n \times D^{n+1}, S^n \times S^n) \xrightarrow{U} Z
\]

where the last map is evaluation of the Thom class $U \in H^{n+1}(S^n \times D^{n+1}, S^n \times S^n)$. Let $a \in H_{n+1}(L/K_0)$. $j^*(\text{exc}^{-1} U)(a) = U(j_* a) = \theta(a)$.

\[
\begin{array}{ccccccc}
H^{n+1}(L, K_0) & \xrightarrow{j^*} & H^{n+1}(L, L_0) & \xleftarrow{} & H^{n+1}(S^n \times D^{n+1}, S^n \times S^n) \\
\downarrow & & \downarrow & & \downarrow U \in \\
\cap [L, K_0 K_1] & \xrightarrow{} & H^{n+1}(L, K_0 \cup K_1) & \xleftarrow{} & \exists x \in \cap [S^n \times D^{n+1}, S^n \times S^n] \\
\downarrow & & \downarrow & & \downarrow & \\
H_n(L, K_1) & \xleftarrow{p_1} & H_n(L, L_0) & \xleftarrow{\text{exc}^{-1}} & H_n(S^n \times S^n) \\
\end{array}
\]

$j^*(\text{exc}^{-1} U) \cap [L, K_0 \cup K_1] = \pi_1(x) \in H_n(L, K_1)$, so
\[ \theta(a) = j^*(\text{exc}^{-1}U)(a) = \pi_1(x) \cdot (a), \]

where \( \cdot \) denotes algebraic intersection.

Lemma 3. If we set \( y = i^* d(\lambda) \), then:

1. \( H_n(L', K_0)/(y) \cong H_n(L, K_0)/(x_0), \langle y \rangle \) means “subgroup generated by”.

2. Suppose \( (x_0) \) has finite order \( s \), then for some \( t \in \mathbb{Z} \) \( sd'(\lambda') + td(\lambda) = 0 \). Order \( y = t \) iff \( t \neq 0 \).

3. If \( n \) is even (as in Theorem 2), \( t = 0 \).

4. If \( n \) is odd (as in Theorem 1), \( L' \) is not uniquely determined, and may be varied to \( L_m' \) by changing the framing of the surgery along \( x \) by \( m \) times the generator of \( \ker(\pi_n(SO(n + 1)) \to \pi_n(SO)) = \mathbb{Z} \). So \( t \) is a function of \( L_m' \). We have the relation: \( t(L_m') = t(L') + 2ms \).

Proof. These facts correspond to Lemmas 3.2, 3.5, 3.8 and 3.11 respectively in Chapter IV of [1].

Lemma 4. \( L^{2n} \to \frac{\ell}{M} \) is normally bordant rel \( \partial \) to \( L' \) satisfying \( H_*(L', K_0) = 0, * \leq n - 1 \) and \( H_n(L', K_0) \otimes_{\mathbb{Z}_p} = 0 \). (This lemma holds for \( n \) even or odd.)

Proof. In Lemma 1 set \( F = Q \), normal surgery on the classes \( \{a_1, \cdots, a_k\} \) affords the desired \( L' \). More precisely, assume \( \text{Rank}_\mathbb{Z}(H_n(L, K_0)) > 0 \). By setting \( F = Q \) and \( a_i = x \) in Lemma 1, \( \pi_n(x) = x_i \) and \( \pi_1(x) = x_1 \) are infinite order. Therefore, by diagram (\( \star \)) \( \langle x_0 \rangle = \mathbb{Z} \) and \( \langle y \rangle = \text{torsion} \). Let \( L' \) result from surgery on \( x \). Now (1) of Lemma 3 implies \( \text{Rank}_\mathbb{Z}(H_n(L', K_0)) = \text{Rank}_\mathbb{Z}(H_n(\tilde{L}, K_0)) - 1 \). Proceed inductively.

Remark 3. It may not be possible to do the preceding construction without increasing the order of torsion \( (H_n(L, K_0)) \). The reason is that there are diagrams, for example:

\[
\begin{array}{ccc}
Z & \xrightarrow{a + 4b} & Z \\
\downarrow & & \downarrow \\
\pi_0 & & \\
\Delta a \times b & & \\
\end{array}
\]

so that \( x \in Z \oplus Z \) with \( \pi_e(x) \) generating a free summand. So unlike the classical case, killing the free part may increase the torsion!

Lemma 4'. Given a prime, \( p, L^{2n} \to \frac{\ell}{M} \) is normally bordant rel \( \partial \) to \( L' \) such that \( H_*(L', K_0) = 0, * \leq n - 1 \), and \( H_n(L', K_0) \otimes \mathbb{Z}_p = 0 \). (This lemma holds for \( n \) even or odd.)
Proof. Assume $L$ satisfies the conclusion of Lemma 4. In Lemma 1 set $F = \mathbb{Z}_p$ and $a_1 = x$. Now consider diagram (*) with $\mathbb{Z}_p$ coefficient. The mod $p$ reductions $(\pi_0(x))_p = (x_0)_p \in H_n(L, K_0; \mathbb{Z}_p)$ and $(\pi_1(x))_p = (x_1)_p \in H_n(L, K_1; \mathbb{Z}_p)$ are nonzero. $d$ is the zero map so by (1) of Lemma 3:

$$\text{Rank}_{\mathbb{Z}_p}(H_n(L, K_0; \mathbb{Z}_p)) = \text{Rank}_{\mathbb{Z}_p}(H_n(L', K_0; \mathbb{Z}_p)) + 1.$$  

Using the U.C.T. and $H_{n+1}(L^0, K_0; \mathbb{Z}) = 0$ we have:

$$\text{Rank}_{\mathbb{Z}_p}(H_n(L, K_0; \mathbb{Z}) \otimes \mathbb{Z}_p) = \text{Rank}_{\mathbb{Z}_p}(H_n(L', K_0) \otimes \mathbb{Z}_p) + 1.$$  

Lemma 4' now follows by induction on the above rank.

The argument is now restricted to $n = \text{odd}$. The prime 2 will play a special role.

Let $L$ satisfy $H_*(L, K_0) = 0$, $* \leq n - 1$ and $H_n(L, K_0) \otimes \mathbb{Z}_2 = 0$ (i.e., $H_n(L, K_0)$ is odd torsion).

**Lemma 5.** If $n$ is odd and $L$ is as above, and if a prime $p$/order $(H_n(L, K_0))$ there is a normal bordism rel $\partial L$ to $L'$ (consisting of either one or two normal $n$-surgeries) with: (1) $H_*(L', K_0) = 0$, $* \leq n - 1$, (2) $H_n(L', K_0)$ odd torsion, and either: (3) order $H_n(L', K_0) \leq \text{order } H_n(L, K_0)$, and (4) $\text{Rank}_{\mathbb{Z}_p}(H_n(L', K_0) \otimes \mathbb{Z}_p) < \text{Rank}_{\mathbb{Z}_p}(H_n(L, K_0) \otimes \mathbb{Z}_p)$ or (3') order $H_n(L', K_0) < \text{order } H_n(L, K_0)$.

**Proof.** In Lemma 1 set $F = \mathbb{Z}_p$ and $a_1 = x$. As in the proof of Lemma 4', any normal surgery based on $x$ results in an $L'$ with $\text{Rank}_{\mathbb{Z}_p}(H_n(L', K_0) \otimes \mathbb{Z}_p) < \text{Rank}_{\mathbb{Z}_p}(H_n(L, K_0) \otimes \mathbb{Z}_p)$. By (4) of Lemma 3 $\forall m$, $t(L''_m) = t(L'_m) + 2ms$, where $s = \text{order } x_0 \in H_n(L, K_0)$. By (1) and (2) of Lemma 3, $t(L'_m) \neq 0$ iff $H_n(L'_m, K_0) = \text{torsion}$, and order (torsion $H_n(L'_m, K_0)$) $\leq \text{order } H_n(L, K_0)$ iff $-s \leq t(L'_m) \leq s$. If (and only if) $t(L''_m) = 2s$, order $H_n(L', K_0) = 2(\text{order } H_n(L, K_0))$. We may choose $m$ so that: Case A. $t(L''_m) \neq 0$ and $-s \leq t(L'_m) \leq s$ or Case B. $t(L'_m) = 2s$.

In each case diagram (*) with $\mathbb{Z}_2$ coefficients shows $\text{Rank}_{\mathbb{Z}_2}(H_n(L', K_0) \otimes \mathbb{Z}_2) = 0$ or 1. In Case A we are finished if the above rank is zero; assume it is one. If $t(L''_m) = \pm s$, order $H_n(L', K_0) = \text{order } H_n(L, K_0)$, so (2) and (3) above are satisfied and we are finished. So add the assumption: $-s < t(L'_m) < s$. Then order $H_n(L', K_0) < \text{order } H_n(L, K_0)$. Now Lemma 1 with $F = \mathbb{Z}_2$ provides $x' = a_1 \in \ker f: H_n(L') \to H_n(M)$, so that if $L''$ is the result of a normal surgery on $x'$ then $H_n(L'', K_0) \otimes \mathbb{Z}_2 = 0$. $\exists r \in \mathbb{Z}$ such that $-\text{order } x' \leq t(L''_m) \leq \text{order } x'$. However, $t(L''_m) \neq 0$ as this would imply order $H(L'', K_0) = \infty$, contradicting $H_n(L'', K_0) \otimes \mathbb{Z}_2 = 0$. So order $(H_n(L'', K_0)) \leq \text{order } (H_n(L'_m, K_0)) < \text{order } (H_n(L, K_0))$ so (3') above is satisfied. This completes Case A.
In Case B order \( (H_n(L', K_0)) = 2(\text{order } (H_n(L, K_0))) \).

**Lemma 6.** \( \exists x' \in \ker f'_n: H_n(L', M) \to H_n(M) \) such that \( \pi_0(x') \) is the unique element of order 2, \( \delta \), in \( H_n(L', K_0) \) and \( (\pi_1(x'))_2 \neq 0 \).

**Proof.** \( H_n(L', K_0) \cong H_n(L, K_1) \cong Z_2 + \pi \), where \( \pi \) is odd torsion. Consider compositions \( P_0, P_1 \)

\[ \begin{array}{ccc}
\ker f'_n & \overset{\pi_0}{\longrightarrow} & H_n(L', K_0) \\
\downarrow{\pi_1} & & \downarrow{\pi_1} \\
H_n(L, K_1) & \overset{P_0}{\longrightarrow} & H_n(L, K_0) \\
\downarrow{\pi_1} & & \downarrow{\pi_1} \\
Z_2 & \overset{P_1}{\longrightarrow} & 0 \\
\end{array} \]

Ker \( P_0 \not\subset \ker P_1 \), otherwise \( P_1 \) could be factored through \( P_0 \) by an epimorphism (dotted arrow). Let \( x \in \ker P_0 — \ker P_1 \). \( \pi_0(x) = 0 \) or \( \delta \), \( (\pi_1(x))_2 \neq 0 \). If \( \pi_0(x) = \delta \), set \( x' = x \) and we are finished. If \( \pi_0(x) = 0 \) let \( y \in \ker f'_n \) satisfy \( \pi_0(y) = \delta \). If \( (\pi_1(y))_2 \neq 0 \), set \( x' = y \) and we are finished. If \( (\pi_1(y))_2 = 0 \), set \( x' = x + y \). Now \( \pi_0(x') = \pi_0(x + y) = 0 + \delta = \delta \) and \( (\pi_1(x'))_2 = (\pi_1(x + y))_2 = (\pi_1(x))_2 + (\pi_1(y))_2 = 1 + 0 = 1 \).

Let \( L'' \) be the result of a normal surgery along \( x' \). Again looking at \( \text{Rank}_{Z_2} \) tells us \( t(L'') \neq 0,2 \). Therefore we can choose \( r \) so that \( t(L'') = \pm 1 \). It follows from diagram (*) that \( H_n(L'', K_0) \cong H_n(L', K_0)/Z_2 \). \( L'' \) satisfies (3) above, but

\[ \text{Rank}_{Z_p}(H_n(L'', K_0) \otimes Z_p) = \text{Rank}_{Z_p}(H_n(L', K_0)) < \text{Rank}_{Z_p}(H_n(L, K_0)) \]

so \( L'' \) also satisfies (4) above. This completes Case B.

\( \text{Rank}_{Z_p}(H_n(L, K_0) \otimes Z_p) \) is finite so after a finite number of applications of Lemma 5, it is no longer possible to reduce the \( Z_p \)-rank without increasing order \( (H_n(L, K_0)) \). So we can find a normal cobordism rel \( \partial \) of \( L \) to \( L' \) with (1), (2) and (3') satisfied. By inducting on order \( (H_n(L, K_0)) \), we have a normal bordism rel boundary to \( L' \) with \( H_*(L', K_0) = 0 \), all values of \( * \). Theorem 1 now follows from the \( h \)-cobordism theorem.
Proof of Theorem 2. If \( n \) is even, surgery on a torsion class of \( H_n(L, K_0) \) will always increase the rank_\( Z \) \( (H_n(L, K_0)) \) (see Lemma IV.3.8 of [1]). Remark 3 shows that it may be impossible to do surgery to lower \( \text{Rank}_Z (H_n(L, K_0)) \) without increasing order (torsion \( H_n(L, K_0) \)). This prevents the usual inductive argument on order torsion \( H_n(L, K_0) \), and is the reason that Theorem 2 requires an additional assumption.

Let \( \{\alpha_0^i, \ldots, \alpha_k^i\} \subset \ker f_0^i : H_n(K_0) \to H_n(M) \) be a basis for \((\ker f_0^i ; Z)/\text{torsion} \) and let \( \{\alpha^i_1, \ldots, \alpha^i_l\} \subset (\ker f_1^i, Z) \) be the isometric image of \( \{\alpha_0^i, \ldots, \alpha_k^i\} \). By the relative Hurewicz Theorem, the \( \alpha \)'s are spherical. The classes \( \{ (i_0^i.(\alpha_0^i) - i_1.(\alpha_1^i), \ldots, i_0^i.(\alpha_k^i) - i_1.(\alpha_1^i) \} \) are represented by framed, imbedded \( n \)-spheres, \( s_1, \ldots, s_k \). Let \( L' \) be the result of a normal surgery on \( \{s_1, \ldots, s_k\} \). Let \( h_0, h_1 \) denote the inclusions \( K_0 \to L', K_1 \to L' \).

**Lemma 7.** \( h_0.(\ker f_0^i ; Z) = h_1.(\ker f_1^i ; Z) \) in the quotient \( H_n(L'; Z)/\text{torsion} \).

**Proof.** By induction on the number of surgeries. We will denote the inclusions at any stage by \( \text{inc}_0 \) and \( \text{inc}_1 \). Surgery on \( s_i \) makes \( \text{inc}_0(\alpha_0^i) = \text{inc}_1(\alpha_1^i) \). Assume that after surgery on \( s_1, \ldots, s_j \), \( \text{inc}_0(\alpha_0^i) = \text{inc}_1(\alpha_1^i) \), \( 1 \leq i \leq j \). Let \( b_1, \ldots, b_n \) be simplicial chains with \( \partial b_i = \alpha_0^i \cup -\alpha_1^i \). Let \( \cap \) denote algebraic intersection. \( \cap_{L}(s_{i+1}, b_i) = \cap_{K_0}(\alpha_0^{i+1}, \alpha_0^i) + \cap_{K_1}(\alpha_1^{i+1}, \alpha_1^i) = 0 \) (using the isometry). As a result, \( \text{inc}_0(\alpha_0^i) \) and \( \text{inc}_1(\alpha_1^i) \) remain equal after surgery on \( s_{i+1} \) and \( \text{inc}_0(\alpha_0^{i+1}) = \text{inc}_1(\alpha_1^{i+1}) \). The lemma follows.

Consider the following diagram with all kernels interpreted by applying the function \( H_n(\ ; Z) \).

\[
\begin{array}{ccc}
0 & \xrightarrow{\text{ker } f/ h_1.(\ker f_1^i)} & H_n(L, K_1) \\
\downarrow & & \downarrow \\
\downarrow & & \downarrow \\
\text{ker } f & \xrightarrow{\pi_1} & \text{ker } f \\
\downarrow & & \downarrow \\
\text{ker } f/ h_0.(\ker f_0^i) & \xrightarrow{\pi_0} & H_n(L, K_0) \\
\downarrow & & \downarrow \\
0 & \xrightarrow{\text{ker } f/ h_0.(\ker f_0^i)} & H_n(L, K_0) \\
\end{array}
\]

Lemma 7 implies \( h_1(\ker f_1^i) = h_0(\ker f_0^i) \) in the quotient \( (\ker f)/\text{torsion} \).

Assuming the hypothesis of Theorem 2, we have:

**Lemma 8.** Suppose \( h_1(\ker f_1^i) = h_0(\ker f_0^i) \) in the quotient \( (\ker f)/\text{torsion} \). If \( \text{Rank}_Z H_n(L, K_0) > 0 \) \( \exists x \in \ker f \) such that
(1) $\pi_\varepsilon(x) = x_\varepsilon$ generates a free summand of $H_n(L, K_\varepsilon)$, for $\varepsilon = 0, 1$, and

(2) If $L'$ is the result of surgery on $x$, $h_i(\ker f_i) = h_0(\ker f_0)$ in the quotient $(\ker f')/\text{torsion}$.

(3) $H_n(L, K_0) \cong H_n(L', K_0) \oplus \mathbb{Z}$.

**Proof.** Let $y \in H_n(L, K_0)$ generate a free summand. Let $x' \in \ker f$ satisfy $\pi_\varepsilon(x') = y$. $\pi_\varepsilon(x')$ generates a free summand of $H_n(L, K_\varepsilon)$ (Proof: Consider the above diagram modulo torsion.). Let $b_n, 1 \leq i \leq k$, be as before. Let $a_i = \cap(x', b_i)$. Since $(\ker f_0, \cap)$ is nonsingular, $\exists \beta \in \ker f_0$ such that $\cap_{\alpha_i}(\beta, \alpha_i) = -a, \forall 1 \leq i \leq k$. Set $x = x' + i_0(\beta)$. $\cap(x', b_i) = 0 \forall b_i$. (2) now follows. It is easy to check (3) using diagram (*) of Lemma 2. (Compare with Remark 3.)

Let $(L'; K_0, K_1)$ be a normal bordism satisfying the conclusion of Lemma 7. By virtue of Lemma 8, we may do surgery to eliminate $H_n(L', K_0)$. The argument for this coincides with "the proof of Theorem IV.2.1 for $m = 2q + 1, q$ even", page 104, [1]. As before, $L'$ becomes an $h$-cobordism completing the proof of Theorem 2.

**Remark 4.** If $n = 2$, this argument may be used to give another proof of: homotopy equivalence $\Rightarrow$ $h$-cobordism for simply connected 4-manifolds, see Wall, [4].

The *Proof of Theorem 3*. We may again assume $H_*(L, K_0) = 0$, $* \neq n, n + 1$. $L$ may be described as $K_0 \times I \cup n, n + 1$-handles. Let $D^\pm$ be the cores of the $n$-handles. Disks $D^-_i \to K_0 \times I$ may be chosen so that $f\# [D^+_i \cup D^-_i] = 0 \in \pi_n(M)$ as $f\#: \pi_{n-1}(K_0) \to \pi_{n-1}(M)$ is an isomorphism and $f\#: \pi_n(K_0) \to \pi_n(M)$ is surjective. Let $H$ be the level set of $L$ after the $n$-handles have been attached. The preceding statement implies that $H$ is obtained from $K_0$ by a sequence of surgeries on $(n - 1)$-spheres, $\partial D^-_i$, trivialized by some null-homotopy $(D^-_i)$ in $K_0 \times I$. By general position $\{\partial D^-_i\}$ is isotopically trivial (we check $(n - 1) + 1 < \frac{1}{2}(2n + 1)$). Therefore, $H \cong K_0 \#_i (S^n \times S^n)$. By turning $L$ upside down, we obtain $H \cong K \#_k (S^n \times S^n)$. This proves Theorem 3.

**References**


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